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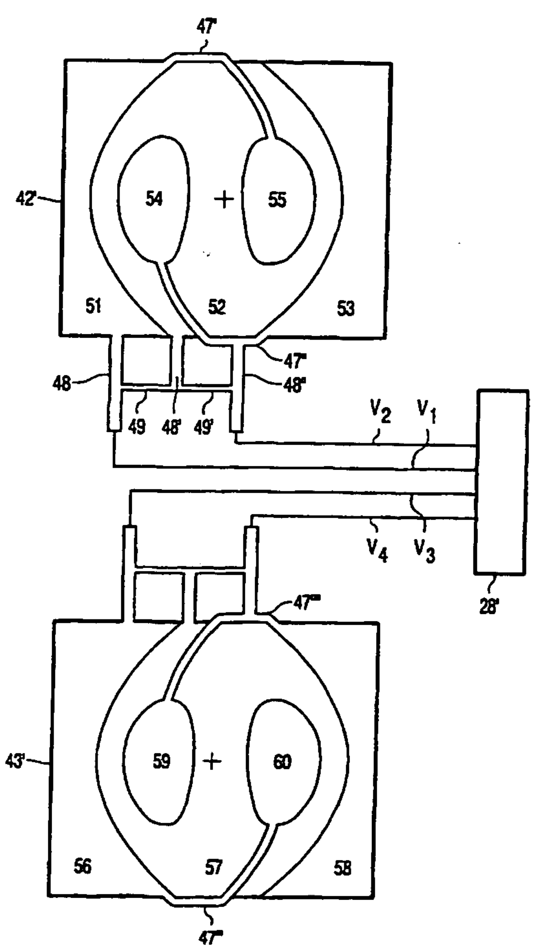

(57) Abstract: An optical wavefront modifier (27) is adapted for modifying a wavefront of an optical beam passing through the modifier. The modifier comprises a first and a second transparent electrode layer (42', 43') and a flat medium (46) for modifying the wavefront in dependence on electrical excitation and arranged between the electrode layers. The first electrode layer (42') comprises three or more electrodes (51-55) of a transparent, conductive material. The electrode layer also comprises a series arrangement of resistors, comprising three terminals (48, 48', 48") connected to the electrodes and resistors (49, 49') connecting the terminals. The resistors are made of the same transparent conductive material as the electrodes.

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Optical wavefront modifier

The invention relates to an optical wavefront modifier for modifying a wavefront of an optical beam passing through the modifier, the modifier comprising a first and a second transparent electrode layer and a medium for modifying the wavefront in dependence on electrical excitation of the medium and arranged between the electrode layers, the first electrode layer comprising three or more electrodes of a transparent, conductive material.

An optical wavefront modifier may be used to change the properties of an optical beam, for instance changing its vergence by introducing a focus curvature in the wavefront of the beam or changing the direction of the beam by introducing tilt. A wavefront modifier may also operate as a wavefront compensator for compensating an undesired shape of the wavefront of an optical beam, e.g. for removing spherical aberration or coma from a wavefront.

European Patent Application No. 0 745 980 shows an optical scanning head using an optical wavefront modifier as wavefront compensator for compensating coma. The compensator uses an electrostriction medium arranged in the optical path between the radiation source and the objective system. One of the electrode layers of the compensator comprises three electrodes of a transparent material, each of the electrodes being electrically connected to a control circuit. A disadvantage of the known modifier is the relatively large number of electrical connections to be made between the modifier and the control circuit.

It is an object of the invention to provide a modifier that requires a reduced number of electrical connections for its control.

This object is achieved if, according to the invention, the first electrode layer comprises a series arrangement of resistors, the electrodes being electrically connected to the series arrangement of resistors and the resistors being made of said transparent, conductive material. The invention is based on the recognition, that the voltages used for controlling the separate electrodes of the modifier have such a mutual dependence, that the voltages can be derived from a series arrangement of resistors. When this series arrangement of resistors is integrated in an electrode layer of the modifier, the only voltages to be applied to the modifier are the voltages to be connected to the terminals of the series arrangement, thereby

reducing the number of electrical connections to the modifier. The number of terminals in a configuration is two for simple electrode configurations and may be three or more for more elaborate configurations. The integration of the series arrangement in the electrode layer also simplifies the manufacture of the modifier.

Preferably, the series arrangement comprises three terminals for supplying control voltages to the series arrangement. This allows a division of the electrodes in the configuration in two groups, each group being controlled independently of the other group.

The electrodes have preferably a configuration for imparting a wavefront modification in Seidel form. In the Seidel form the electrodes extend from one side of the cross-section of the optical beam to the other side for most optical aberrations, allowing an easy connection to the series arrangement of resistors. In contrast, wavefronts in Zernike form require in general electrode shapes where one electrode is completely surrounded by another electrode; an electrical connection to the surrounded electrode must be made by a small strip through the surrounding electrode, thereby disturbing the electrode pattern.

A further aspect of the invention relates to a device for scanning an optical record carrier having an information layer, comprising a radiation source for generating a radiation beam, an objective system for converging the radiation beam through the transparent layer to a focus on the information layer, and a detection system for intercepting radiation from the record carrier, wherein an optical wavefront modifier is arranged in the optical path between the radiation source and the detection system, which modifier comprises a first and a second transparent electrode layer and a flat medium for modifying the wavefront in dependence on electrical excitation of the medium and arranged between the electrode layers, the first electrode layer comprising three or more electrodes of a transparent, conductive material, and the first electrode layer comprises a series arrangement of resistors, the electrodes being electrically connected to the series arrangement of resistors and the resistors being made of said transparent, conductive material. The modifier is particularly suitable for use in a scanning device. The radiation source, modifier and objective system are generally integrated in an optical head, which moves with respect to the chassis of the scanning device, in which the control circuit is arranged, in order to follow tracks on the record carrier. A reduction of the number of electrical connections between the optical head and the chassis facilitates the movement of the optical head.

The objects, advantages and features of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings, in which

Figure 1 shows a scanning device according to the invention;

Figure 2 shows two laterally displaced comatic wavefront distortions WD and the difference DIFF between them as a function of radial position r in the radiation beam;

Figure 3 shows a cross-section of an aberration compensator in the form of a liquid crystal cell;

Figure 4A shows an electrode configuration for introducing decentred coma;

Figure 4B shows two superposed electrode configurations for introducing decentred coma;

Figure 5 shows electrical connections between the electrode configurations of Figure 4A and a control circuit;

Figures 6A and B6 show two embodiments of a control circuit for the electrode configurations of Figure 4A;

Figure 7 shows an electrode configuration for introducing decentred coma;

Figure 8A shows the value of the control voltages on the electrodes in the configuration of Figure 7;

Figure 8B shows the dependence of the asymmetry factors p_+ and p_- on the displacement of the objective system;

Figures 9 and 10 show a series arrangement of resistors connecting electrodes in an electrode configuration;

Figure 11 shows an electrode configuration for introducing decentred coma and having the series arrangement of resistors integrated in the electrodes;

Figure 12 shows an electrode configuration for introducing centred astigmatism;

Figure 13 shows a control circuit for an aberration compensator having electrode configurations for both coma and astigmatism; and

Figure 14 shows an electrode configuration for introducing spherical aberration.

Figure 1 shows a device for scanning an optical record carrier 1. The record carrier comprises a transparent layer 2, on 1 side of which information layer 3 is arranged.

The side of the information layer facing away from the transparent layer is protected from environmental influences by a protection layer 4. The side of the transparent layer facing the device is called the entrance face 5. The transparent layer 2 acts as a substrate for the record carrier by providing mechanical support for the information layer. Alternatively, the transparent layer may have the sole function of protecting the information layer, while the mechanical support is provided by a layer on the other side of the information layer, for instance by the protection layer 4 or by a further information layer and a transparent layer connected to the information layer 3. Information may be stored in the information layer 3 of the record carrier in the form of optically detectable marks arranged in substantially parallel, concentric or spiral tracks, not indicated in the Figure. The marks may be in any optically readable form, e.g. in the form of pits, or areas with a reflection coefficient or a direction of magnetisation different from their surroundings, or a combination of these forms.

The scanning device comprises a radiation source 6, for example a semiconductor laser, emitting a diverging radiation beam 7. A beam splitter 8, for example a semitransparent plate, reflects the radiation beam towards a collimator lens 9, which converts the diverging beam 7 into a collimated beam 10. The collimated beam 10 is incident on objective system 11. The objective system may comprise one or more lenses and/or a grating. The objective system 11 has an optical axis 12. The objective system 11 changes the collimated beam 10 to a converging beam 13, incident on the entrance face 5 of the record carrier 1. The converging beam 13 forms a spot 14 on the information layer 3. Radiation reflected by the information layer 3 forms a diverging beam 15, transformed into a collimated beam 16 by the objective system 11 and subsequently into a converging beam 17 by the collimator lens 9. The beam splitter 8 separates the forward and reflected beams by transmitting at least part of the converging beam 17 towards a detection system 18. The detection system captures the radiation and converts it into electrical output signals 19. A signal processor 20 converts these output signals to various other signals. One of the signals is an information signal 21, the value of which represents information read from the information layer 3. The information signal is processed by an information processing unit for error correction 86. Other signals from the signal processor 20 are the focus error signal and radial error signal 22. The focus error signal represents the axial difference in height between the spot 14 and the information layer 3. The radial error signal represents the distance in the plane of the information layer 3 between the spot 14 and the centre of a track in the information layer to be followed by the spot. The focus error signal and the radial error signal are fed into a servo circuit 23, which converts these signals to servo control signals 24

for controlling a focus actuator and a radial actuator respectively. The actuators are not shown in the Figure. The focus actuator controls the position of the objective system 11 in the focus direction 25, thereby controlling the actual position of the spot 14 such that it coincides substantially with the plane of the information layer 3. The radial actuator controls the position of the objective lens 11 in a radial direction 26, thereby controlling the radial position of the spot 14 such that it coincides substantially with the central line of track to be followed in the information layer 3. The tracks in the Figure run in a direction perpendicular to the plane of the Figure.

The scanning device of Figure 1 has a relatively large tolerance range for tilt of the optical record carrier 1. It thereto determines the aberration caused by the tilted record carrier in the converging beam 13, and compensates the aberration by introducing a wavefront distortion in the collimated beam 10. The wavefront distortion is introduced by an aberration compensator 27 arranged in the collimated beam 10. A control circuit 28 controls the wavefront distortion via control signals 29. The value of the aberration to be compensated is determined by an aberration detector, which, in this embodiment, is a tilt detector 30. The tilt detector emits a radiation beam 31 towards the optical record carrier 1 and detects the angle of the beam reflected by the record carrier. The position of the spot of the reflected beam is a measure for the angle and, hence, for the tilt of the record carrier. The measured tilt is directly proportional to the coma in the converging beam 13. Hence, the tilt signal 32, i.e. the output signal of the tilt detector 30, can be used directly as input for the control circuit 28, thereby controlling the amount of coma introduced by the aberration compensator 27.

The tilt detector 30 may be of any type. The tilt signal may also be derived from a combination of detector output signals 19. In that case the tilt detector forms part of the control circuit 28.

The wavefront distortion introduced by the aberration compensator 27 will only compensate the aberration introduced by the tilted record carrier if the introduced aberration is correctly centred with respect to the objective system 11. The compensation is not correct anymore, if the introduced aberration is centred on the axis of collimated beam 10 and the objective system is displaced in a radial direction 26 because of radial tracking. The effect of this displacement is shown in Figure 2, giving wavefronts in that radial cross-section of the radiation beam in which the objective system 11 has its radial displacement d. The displacement d is normalised on the radius of the entrance pupil of the objective system. Drawn curve 37 represents a comatic wavefront distortion WD, centred on the optical axis of the radiation beam 10 at r=0 and introduced by the aberration compensator 27. The dashed

line 38 represents the comatic wavefront distortion to be compensated and caused by the tilted optical record carrier 1, and displaced from the optical axis by a distance d due to a displacement of the objective system 11. It is clear from the Figure that, when the displacement d is zero, the introduced aberration 37 will perfectly cancel the aberration 38, thereby providing a spot 14 on the information layer 3 of the record carrier 1 of high quality. When the displacement d is not equal to zero, the wavefronts 37 and 38 will not cancel each other, thus causing an imperfect compensation. The resulting wavefront error DIFF is the difference between curves 37 and 38, shown in Figure 2 as line 39. For small displacements d, the difference 39 is proportional to the derivative of line 37 with respect to the co-ordinate in the direction of the displacement. The resulting wavefront error is one radial order lower than the wavefront WD, and in this case is astigmatism, the value of which is proportional to the displacement d and the amount of coma to be compensated. This astigmatism must also be compensated by the aberration compensator 27. A more detailed analysis of the wavefront errors shows, that a decentred comatic wavefront not only introduces astigmatism but also a small amount of wavefront tilt and defocus. The wavefront tilt and defocus will be corrected automatically by the radial and focus servo respectively.

The measurement of the position of the objective system 11 in the radial direction 26, required as input for the aberration compensation, is performed by a position detector 33 as shown in Figure 1. A position signal 34 generated by the position detector is used as input for the control circuit 28. The position of the objective system 11 may be measured using any known position measuring method. An optical method is preferred, because it does not affect the mechanical properties of the objective system. The position may also be derived from the detector output signals 19, as is known inter alia from U.S. Patent 5,173,598 (PHN 13695). In that case the position detector forms a part of the signal processor 20.

Figure 3 shows an embodiment of the aberration compensator, in the form of a liquid crystal cell. The cell comprises two plane parallel transparent plates 40 en 41, made of for instance glass. On the inner sides of the transparent plates transparent electrode layers 42 and 43 are arranged. The inner sides of the electrode layers are covered with alignment layers 44 and 45 respectively. A nematic liquid crystal material 46 is arranged between the two alignment layers. The liquid crystal material may be replaced by a ferro-electric medium, when higher switching speeds are required. The electrode layer comprises transparent conductors, made of for instance indium tin oxide. The refractive index of the liquid crystal material is controlled by the voltage difference between the electrode layers 42 and 43. Since

the refractive index determines the optical path length through the liquid crystal layer 46, a temporal and/or spatial variation of the voltage difference can be used to change the wavefront of a radiation beam passing through the aberration compensator. Although the Figure shows a medium in the form of a flat liquid crystal layer, the medium may be curved. The thickness of the medium may vary as a function of position in the cross-section of the radiation beam, thereby reducing the requirements imposed on the control voltages.

Figure 4A shows the electrode structures in electrode layer 42 and 43. These electrode structures are adapted to introduce off-centre coma in the radiation beam. The electrode structures comprise various electrodes in the form of electrically conducting transparent regions separated by small non-conducting intermediate regions, not shown in the Figure. The electrode layer 42 comprises electrodes 51 to 55. Similarly, the electrode layer 43 comprises electrodes 56 to 60. The Figure shows a plan view of the electrode layers 42 and 43. The intersection of the optical axis 35 of collimated beam 10 with the electrode layers is indicated by the cross 50. The electrode structure is adapted to introduce a comatic wave front aberration in the radiation beam passing through the liquid crystal cell in the form of the Zernike polynomial $(3r^3 - 2r) \cos \theta$, where r-θ are the polar co-ordinates in the cross-section of the radiation beam. The angle θ is zero along the horizontal direction in the Figure, from the cross 50 towards electrode 54. The width and position of electrode 54 is indicated by the dot and dash line 36 in Figure 2. The width is chosen such that the electrode 54 covers those regions of the aberration compensator where the value of the Zernike polynomial $(3r^3 - 2r) \cos \theta$ is larger than a predetermined value 'a'. In practice, 'a' has a value between 0.1 and 0.35, and preferably has a value approximately equal to 0.25. The same applies to the other electrodes. The electrode structure in layer 42 is offset in the left direction with respect to the centre 50. The electrode structure in the electrode layer 43 is offset to the right with respect to the centre 50. The amount of offset is determined by the maximum displacement of the objective system 11. Figure 4B shows a plan view of both electrode layers 42 and 43 superposed. The offset of the electrode structures is in the radial direction 26 as indicated in Figure 1.

Figure 5 shows a plan view of electrode layers 42' and 43', which have an electrode configuration similar to the electrode layers 42 and 43, respectively, but with additional electrical connections between the separate electrodes. The electrodes 51 and 55 are electrically connected by a narrow strip electrode 47'. The width of the strip electrode should be sufficiently small so as not to affect the operation of electrode 52; on the other hand, the width should be large enough to avoid reduction of the switching time of the

aberration compensator. Likewise, electrodes 53 and 54, 56 and 60, 58 and 59 are pairwise electrically connected by strip electrodes 47", 47'" and 47"", respectively. The three voltages required for the control of the electrodes in electrode layer 42' are applied by means of three terminals 48, 48' and 48". The end terminals 48 and 48" are connected to the central terminal 48' by means of two narrow strip electrodes 49 and 49', respectively. The strip electrodes 49 and 49' form resistors, which, together with the terminals, form a series arrangement of resistors. The control circuit 28' provides the control signals 29, four of which are indicated in Figure 5 by V_1, V_2, V_3 and V_4. Control signal V_1 is applied to terminal 48 and V_2 to terminal 48". Since the resistance value of electrodes 49 and 49' is chosen to be equal, the voltage at terminal 48' is the average of the voltages on terminals 48 and 48". Control signals V_3 and V_4 are applied to a series arrangement of resistors on electrode layer 43', the series arrangement being similar to that on electrode layer 42'.

The aberration compensator 27 may be controlled by applying various DC voltages to its electrodes. However, it is preferred to use AC voltages for the control in view of the stable operation of the liquid crystal. Figure 6A stable operation shows an embodiment of the control circuit 28, providing AC control voltages for the electrodes in the layout shown in Figure 5. The tilt signal 32 is used as input for a voltage to voltage converter 61, which provides at its output a first control signal 62, having a value ΔV, dependent on the tilt signal 32. The first control signal 62 is connected to an adder 63. A voltage source 63' provides a reference voltage V_0 to the adder 63. The adder has two output signals D_1 and D_2, the values of which are $V_0 + \Delta V$ and $V_0 - \Delta V$, respectively. The two output signals D_1 and D_2 are used as input for a multiplier 64. A square-wave generator 64' provides a square wave signal, having a fixed amplitude and a predetermined frequency, preferably lying in the range between 1 and 10 kHz. This square-wave signal is used as input for the multiplier 64. The multiplier provides two AC control voltages A_1 and A_2 as output signals. Each of the two output signals has a square-wave form and a zero average value. The peak-peak amplitude of signal A_1 is equal to $V_0 + \Delta V$, that of signal A_2 is equal to $V_0 - \Delta V$. The sign and magnitude of the control signals A_1 and A_2 are such, that, when applied to the aberration compensator 27, the correct amount of coma is introduced in the collimated beam 10 to compensate the coma caused by the amount of tilt of the optical carrier 1 as represented by the tilt signal 32. Thereto, the value ΔV is proportional to the value of the tilt signal. The control signals A_1 and A_2 are connected to four change-over switches 65, which have the signals V_1 to V_4 as output signals. The four output signals V_1 to V_4 can be switched between the control signal A_1 or A_2 and ground. The switches 65 are controlled by a switch control circuit 66, which has

the position signal 34 as input. When the position signal is positive, the four switches 65 are in the positions as shown in Figure 6A. When the position signal is negative, the four switches are in their other positions. Hence, in the drawn position of the switches, the electrodes 56-60 are all connected to the ground, and varying voltages are applied to the electrodes 51 to 55. The voltage applied to electrodes 51 and 55 is $V_0 + \Delta V$, to electrodes 53 and 54 $V_0 - \Delta V$, and to electrode 52 via the series arrangement V_0. The voltages are such that a comatic wavefront aberration is introduced which is offset to the left hand side in Figure 5 with respect to the optical axis 35. When the sign of the position signal 34 reverses, the electrodes 51 to 55 are connected to the ground, and the varying voltages are applied to the electrodes 56 to 60. The resulting comatic wavefront aberration is offset to the right hand side with respect to axis 35. The value of the predetermined voltage V_0 depends on the properties of the aberration compensator 27, in particular the liquid crystal material, and is chosen such that the response of the compensator is proportional to ΔV.

Figure 6B shows an alternative embodiment of the control circuit 28. The tilt signal 32 is used as input for a voltage-to-voltage converter 161, which provides at its output a first control signal having a value $\frac{1}{2}\Delta V$, proportional to the amount of tilt. The tilt signal 32 and the position signal 34 are used as input for a multiplier 160, which provides at its output a second control signal having a value of $\frac{1}{2}(x/x_0)\Delta V$, where x is proportional to the displacement of the objective system and x_0 is the maximum displacement of the objective system. The first and second control signal are fed into an adder 162, forming two output signals $\Delta V_1 = \frac{1}{2}\Delta V - \frac{1}{2}(x/x_0)\Delta V$ and $\Delta V_2 = \frac{1}{2}\Delta V + \frac{1}{2}(x/x_0)\Delta V$. A voltage source 165 provides a reference voltage V_0 to an adder 163. The adder also has the signals ΔV_1 and ΔV_2 as inputs and forms four signals having the values $V_0 - \Delta V_1$, $V_0 + \Delta V_1$, $V_0 - \Delta V_2$ and $V_0 + \Delta V_2$. A square-wave generator 166 provides a square wave signal, having a fixed amplitude and a predetermined frequency, preferably lying in the range between 1 and 10 kHz. The square wave signal and the five signals are used as input for a multiplier 164. The multiplier provides six AC control signals V_1 to V_4, which are connected to the aberration compensator 27. Each of the AC control signals has a square-wave form and a zero average value. The peak-peak amplitude of the signals V_1 to V_4 is $V_0 - \Delta V_1$, $V_0 + \Delta V1$, $V_0 - \Delta V_2$ and $V_0 + \Delta V_2$, respectively. The signals V_1 and V_2 have the same phase; likewise V_3 and V_4. The two groups of signals may have the same phase or may be mutually 180° out of phase. The amplitudes of V_0, ΔV_1 and ΔV_2 depend on the properties or the aberration compensator and

the phase between the groups of signals, and are chosen such that the response of the compensator is proportional to ΔV_1 and ΔV_2.

A proper balancing of aberrations in this embodiment of the aberration compensator requires that the displacement between the two electrode structures in the electrode layers 42 and 43 is equal to approximately half the maximum peak-peak displacement of the objective system 11. If the maximum peak-peak displacement of the objective system is e.g. from –400 to +400 μm, the displacement between the electrode structures is preferably 400 μm.

The match between the wavefront aberration introduced by the aberration compensator 27 and the Zernike polynomial for coma may be improved by increasing the number of electrodes in the electrode layers 42 and 43. Figure 7 shows an electrode configuration that can be used in the aberration compensator 27. The electrodes form a series of small strips with a small spacing, causing a smooth transition of the refractive index of the liquid crystal material under one electrode to the refractive index of the liquid crystal material under the neighbouring electrode. The reduction of the phase changes between electrodes reduces the higher order aberrations, even when the objective system 11 is positioned off-centre. The particular width of the electrodes of the embodiment, decreasing with increasing radius, as shown in Figure 7 allows the electrodes to be controlled with a voltage that increases linearly with the strip of the electrode. If the 2N+1 strips are numbered consecutively with an index running as –N, -N+1, ...0,1, ...N, then the strip with index j covers that area in the (x,y) plane that comply with

$$\frac{2j-1}{2N+1} \langle \; W_{31}(x,y) \; \langle \; \frac{2j+1}{2N+1}$$

$W_{31}(x,y) = (x^2+y^2)x$ is the Seidel polynomial for coma, and x,y are normalised co-ordinates in the cross-section of the radiation beam in the plane of the aberration compensator, where x is in the direction of displacement of the objective system. This electrode structure introduces a comatic wavefront aberration in the beam passing through the aberration compensator. The aberration is not of the Zernike type but of the Seidel type, which has the advantage of a simpler layout of the electrodes, each electrode having a connection outside the cross-section of the beam, and a simple scheme for the control voltages. The tilt and defocus, which are inherently introduced into the radiation beam 10 when using Seidel aberrations, will be compensated automatically by the focus and radial tracking servo of the device.

The electrode configuration 67 shown in Figure 7 may be used in both electrode layers 42 and 43, and displaced with respect to one another as indicated in Figure 4B. The control of the voltages of the electrodes in the two electrode layers can be carried out by a control circuit similar to the ones shown in Figure 6A and B. In an alternative embodiment, the electrode configuration 67 is arranged in electrode layer 42 and centred on the optical axis 35. The electrode layer 43 comprises a single electrode covering the entire cross-section of the radiation beam 10 and set at a fixed potential. When controlled by a voltage that increases linearly from one electrode to the next, the electrode configuration will give rise to centred comatic wavefront aberration. The astigmatism, required when the objective system 11 is off-centre, can be introduced by an asymmetric control of the electrodes as indicated in Figure 8. Figure 8 shows the voltage as a function of the electrode number, where electrode number zero is the central electrode of the electrode configuration, which is set at a voltage V_0. The drawn line 68 indicates the linearly increasing voltage for the generation of centred coma. The dashed line 69 indicates the voltages for simultaneously generating coma and astigmatism.

The electrode configuration 67 as shown in Figure 7 requires a relatively large number of voltages to be generated by the control circuit 28. The number of voltages to be generated by the control circuit can be reduced, if the electrode configuration is provided with a series arrangement of resistors that forms the required voltages. Figure 7 shows a series arrangement made up of resistors 70, the arrangement being provided with a central terminal 71 and two end-terminals 72 and 73. The three terminals 71, 72 and 73 allow both a control by a linear voltage indicated by drawn line 68 and by a voltage indicated by dashed line 69 in Figure 8A. A more accurate control can be obtained if the number of terminals is increased. The voltages applied to end terminals 72 and 73 may be chosen asymmetrical with respect to the voltage V_0 on the central terminal 71. The voltage Vj on strip j can then be written as

$$V_j = V_0 - p_\pm \frac{j}{N} \Delta V ,$$

where ΔV is equal to $(V_{+N} - V_{-N})/2N$ if there is no displacement of the objective system. The asymmetry factor p_+ is used for $j \geq 0$ and p_- for $j<o$ for one sign of the tilt signal; p_- is used for $j \geq 0$ and p_+ for $j<0$ for the other sign of the tilt signal. The values of the factors depend on the displacement d as indicated in Figure 8B, where the drawn line represents the values of p_+ and the dashed line those of p_-.

Figure 9 shows an electrode configuration wherein the series arrangement of resistors is integrated in the conductive layer of the electrode layer. The embodiment has five electrodes 76-80 separated by small non-conductive strips. The three terminals 81, 82 and 83 are connected by four resistors 84, formed by strips of conductive layer, connected in series between the terminals. A high resistance can be obtained by decreasing the width of the strips that make up the resistors 84. Five taps 85 connect the resistors with the electrodes.

Figure 10 shows an alternative embodiment of the electrode configuration of the aberration compensator 27. The configuration comprises a structure 88 for generation of coma, similar to the structure shown in Figure 7. The individual strips of the structure 88 are connected by taps in the form of strips 89 to a resistor maze 90. The maze forms resistors of equal value between subsequent taps 89. The control voltages are applied to the configuration through terminals 91, 92 and 93. The extent of the maze may be reduced by arranging these strips of the maze in a zigzag structure. Alternatively, the strips of the maze may be arranged around the structure 88.

Figure 11 shows an embodiment 67' of the electrode configuration of the aberration compensator 27 similar to the embodiment shown in Figure 7. The series arrangement of resistors has been integrated in the transparent electrodes. Neighbouring electrodes 79' and 80' are connected by a small strip 81' acting as resistor, made of the same material as the electrodes and running substantially parallel to the non-conducting intermediate region 82' separating the electrodes. This arrangement of the resistors has the advantage, that the electrode structure can be kept relatively small, because the resistors do not require any space in the structure outside the cross-section of the radiation beam. Moreover, the resistors give only a relatively small disturbance of the electrical field pattern generated by the electrodes. The voltages on the three terminals 71', 72' and 73', connected to the central electrode and the two outer electrodes, respectively, can be controlled in the same way as the voltages on the terminals 71, 72 and 73 in Figure 7.

The resistor of the elements in the maze must be sufficiently large to ensure a tolerable low level of dissipations and sufficiently small to ensure an RC-time of the cell that is much smaller than the period of the AC-voltage.

The coma caused by tilt of the record carrier 1 may also be compensated by an aberration compensator that introduces centred coma and centred astigmatism. Thereto, the aberration compensator 27 is provided with electrode layer 42 having an electrode configuration for introducing centred coma, and electrode layer 43 having an electrode configuration for introducing centred astigmatism. The electrode configuration for centred

coma is similar to the electrode configuration 42 shown in Figure 4A but centred on the intersection 50 of optical axis 35. The centred coma may also be introduced by the electrode configuration 67 shown in figure 7.

Figure 12 shows an electrode configuration 95 in electrode layer 43 for introducing centred astigmatism. The electrode pattern is centred on the optical axis 35. A circle 96 in the electrode configuration indicates the cross-section of the radiation beam in the plane of the configuration. The electrodes in both electrode layers may be confined to the area within the beam cross-section 96, or may extend outside the beam cross- section. The configuration 95 is adapted to introduce astigmatism in the Zernike form, which can be described as $Z_{22} = x^2-y^2$. The normalised co-ordinates x,y are indicated in the Figure. This Zernike form for astigmatism is particularly suitable for an aberration compensator which also introduces coma in the Seidel form. In its simplest form, the electrode configuration comprises a central electrode 97 and four side electrodes 98-101. The position of the border between the electrodes and the control voltages is determined as follows. The points in the configuration with $Z_{22}(x,y) > a$ are set at a voltage $V_{10} = V_0' - \Delta V$. The points in the configuration with $-a < Z_{22}(x,y) < a$ are set at a voltage $V_{11} = V_0'$. The points in the configuration with $Z_{22}(x,y) < -a$ are set at a voltage $V_{12} = V_0' + \Delta V$. The voltage ΔV is proportional to the amount of astigmatism to be introduced. The value of the parameter a is preferably in the range from 0.10 to 0.60, and, more preferably, substantially equal to 0.25. The electrode configuration shown in Figure 12 is based on a = 0.25.

Figure 13 shows a control circuit for the electrical control of an aberration compensator having both the electrode configuration 67 for introducing coma in the radiation beam passing through the compensator and the electrode configuration 95 for introducing astigmatism in the beam. The control circuit can also be used if the electrode configurations have both a Zernike layout or both a Seidel layout. The control of the coma configuration 67 is similar to the control shown in Figure 6A and B. Hence, voltage converter 105, first control signal 106, adder 107 and voltage source 108 are similar to the corresponding elements 61 to 64' in Figure 6A. The DC output signals D_4, D_5 and D_6 of adder 107 correspond to the output signals D_1, D_2 and D_3, respectively as shown in Figure 6A. The control of the astigmatism configuration 95 uses the tilt signal 32 and the position 34 as input signals. A multiplier 109 forms the product of the two signals. The product is a measure for the astigmatism introduced into the radiation beam by the combination of a centred comatic aberration introduced by the wavefront compensator 27 and a displaced objective system 11. The product is output as a second control signal 110 and used as input for an adder 111. A

voltage source 112 supplies a voltage V_0' to the adder. The adder has three DC output signals D_7, D_8 and D_9, having the values $V_0'+\Delta V$, V_0', $V_0'-\Delta V$ respectively, where ΔV is the value of the second control signal 110. The DC output signals D_4 to D_9 are connected to a multiplier 113, which forms output signals V_7 to V_{12}. A square–wave generator 114, similar to the square-wave generator 64' in Figure 6A, supplies a square wave signal to the multiplier 113. The multiplier 113 multiplies each of the six input signals D_4 to D_9 with the square-wave signal, resulting in six square wave output signals V_7 to V_{12}, respectively, having the wave form of the output of the square-wave generator 114 and an amplitude corresponding to the signals D_4 to D_9. The output signals V_7, V_8 and V_9 are similar to the output signals A_1, A_2 and A_3, respectively, in Figure 6A, and are connected to the terminals 71, 72 and 73, respectively, of the electrode configuration 67 shown in Figure 7. The output voltage V_{10} is connected to side electrodes 98 and 100 of electrode configuration 95 shown Figure 12. The output voltage V_{11} is connected to the central electrode 97, and the output voltage V_{12} is connected to the side electrodes 99 and 101.

The electrode configuration 95 shown in Figure 12 may also be provided with a series arrangement of resistors similar to the series arrangements shown in Figure 5. The side electrodes 99 and 100 are each connected to an end terminal, whereas the central electrode 97 is connected to a central terminal. Electrodes 98 and 100 are connected by a conducting strip, not shown in the Figure; similarly, the electrodes 99 and 101 are connected. The series arrangement of resistors is formed by two narrow electrode strips acting as resistors between the central terminal and each of the end terminals. This configuration does not require the control voltages V_8 and V_{11} of control circuit 113 shown in Figure 13.

The aberration compensator 27 in the above described embodiments compensates coma caused by tilt of the record carrier 1, taking into account the position of the objective system 11. The position of the objective system can also be taken into account for compensators that introduce aberrations other than coma, for instance spherical aberration, caused for instance by variations in the thickness of the transparent layer 2 of the record carrier one. When an optical beam in which centred spherical aberration has been introduced passes through a displaced objective system, the beam after passage through the objective system will suffer from coma which is linear in the displacement and astigmatism which is quadratic in the displacement of the objective system. The compensation of the spherical aberration can be corrected for the displacement of the objective system in a way similar to the correction in the above described embodiments of the aberration compensator. A first adapted embodiment of the aberration compensator comprises a first electrode layer

having an electrode configuration for generating spherical aberration as shown in Figure 14, the centre of which is displaced with respect to the intersection of the optical axis 35 with the electrode layer, and a second electrode layer having a similar electrode configuration for generating spherical aberration, but displaced in a direction opposite to the configuration in the first electrode layer. A second embodiment of the aberration compensator comprises a first electrode layer having an electrode configuration for generating a centred spherical aberration, and a second electrode layer having an electrode configuration for generating centred coma. The two electrode configurations may also be combined into a single electrode layer. A third embodiment of the aberration compensator comprises three electrode layers and two liquid crystal layers between them. One layer is provided with an electrode configuration for generating centred spherical aberration. A second layer is provided with a configuration for generating centred coma and a third layer with a configuration for generating centred astigmatism. The aberration compensator is controlled by the position signal 34 representing the position of the objective system and a signal representing the amount spherical aberration in the radiation beam returning from the record carrier. A sensor for measuring the spherical aberration in the radiation beam is described in the European Application having filing number 98204477.8 (PHN 17.266).

Figure 14 shows a electrode configuration 116 for generating spherical aberration. The Zernike representation of the aberration is $Z_{40} = 6(x^2+y^2)(x^2+y^2-1)+1$. The borders between the electrodes and the voltages applied to them can be derived as follows. The points in the configuration with $Z_{40}(x,y) > a$, i.e. the central area 117 and the ring 121, are set at a voltage V_0-ΔV. The points in the configuration complying with $-a < Z_{40}(x,y) < a$, i.e. the rings 118 and 120, are set at a voltage V_0. The points in the pupil with $Z_{40}(x,y) < -a$, i.e. the ring 119, are set at a voltage $V_0+\Delta V$. The parameter 'a' is preferably in the range from 0.20 to 0.70. The electrode configuration shown in Figure 14 is for $a = \sqrt{3}/4 = 0.433$. This value of a gives equal surface areas for the electrodes to which a voltage V_0-ΔV is applied and those to which $V_0+\Delta V$ is applied. The electrode configuration for generating spherical aberration may be simplified by forming three concentric rings and applying different voltages to them.

The electrode configurations for generating spherical aberration, coma and/or astigmatism may be combined into a single electrode configuration by a suitable division of the electrode layer into separate electrodes and a corresponding adaptation of the control circuit. The aberration compensator may comprise one electrode layer for introducing two

aberrations, e.g. coma and astigmatism, and one electrode layer for introducing another aberration, e.g. spherical aberration.

Although the above described embodiments of the invention relate to aberration compensators, it will be clear the invention is not limited to these embodiments. The invention can be used in any wavefront modifier, irrespective of correction for transverse displacement of the objective system. The wavefront modifier according to the invention is not limited to wavefront compensators, but include any optical element comprising transparent electrode layers and a medium for modifying the wavefront in dependence on electrical excitation of the medium. An example is a wavefront modifier that introduces a wavefront distortion on the radiation beam that is quadratic in the radius of the wavefront. Such a modifier can be used in a scanning device, wherein an objective system provides for slow and large axial movement of the focus point and the wavefront modifier provides for fast and small axial changes of the focus point. Similarly, the wavefront modifier may introduce tilt in the radiation beam, allowing small displacements of the focus point in a direction perpendicular to the track to be followed by the focus point. This fine movement can be in addition to a coarse movement obtained by a displacement of the objective lens or of the complete optical head.

CLAIMS:

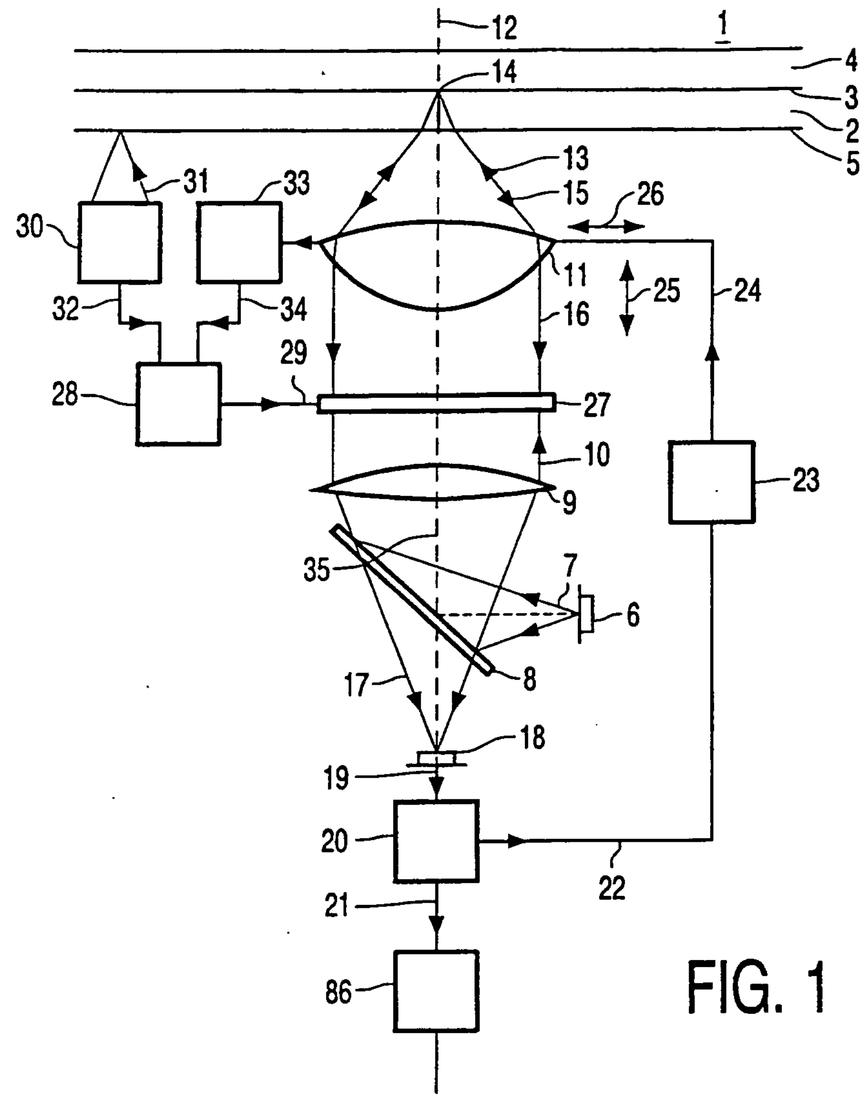
1. An optical wavefront modifier for modifying a wavefront of an optical beam passing through the modifier, the modifier comprising a first and a second transparent electrode layer and a medium for modifying the wavefront in dependence on electrical excitation of the medium and arranged between the electrode layers, the first electrode layer comprising three or more electrodes of a transparent, conductive material, characterized in that the first electrode layer comprises a series arrangement of resistors, the electrodes being electrically connected to the series arrangement of resistors and the resistors being made of said transparent, conductive material.

2. Optical wavefront modifier according to Claim 1, wherein the electrode layer comprises three terminals, which are electrically connected to the series arrangement of resistors.

3. Optical wavefront modifier according to Claim 1, wherein the electrodes have a configuration for imparting a wavefront modification in Seidel form.

4. Optical wavefront modifier according to Claim 1, wherein the series arrangement of resistors is integrated in the electrodes.

5. A device for scanning an optical record carrier having an information layer, comprising a radiation source for generating a radiation beam, an objective system for converging the radiation beam through the transparent layer to a focus on the information layer, and a detection system for intercepting radiation from the record carrier, characterized in that an optical wavefront modifier according to any of the preceding Claims is arranged in the optical path between the radiation source and the detection system.


12
1
14
4
3
2
5
13
15
26
31
33
30
11
25
24
32
34
16
29
28
27
10
23
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35
7
6
8
17
18
19
20
21
22
86

FIG. 1

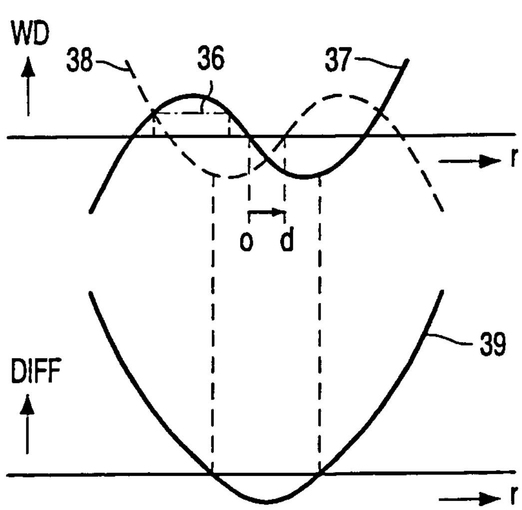
WD
38
36
37
r
o
d
39
DIFF
r

FIG. 2

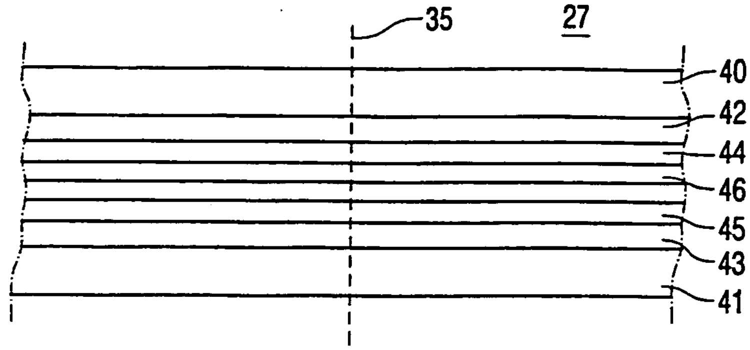

FIG. 3

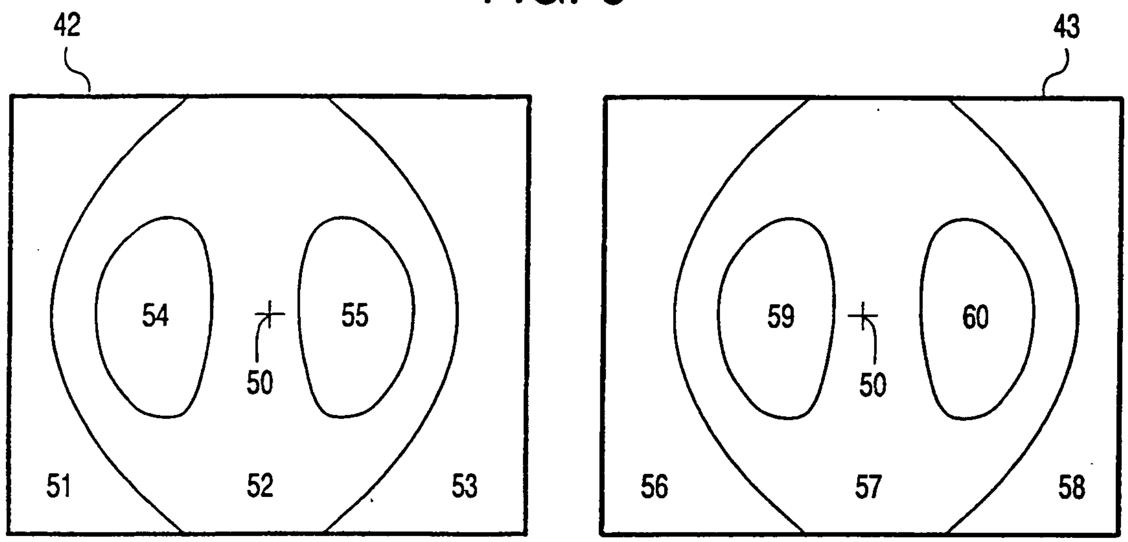

FIG. 4A

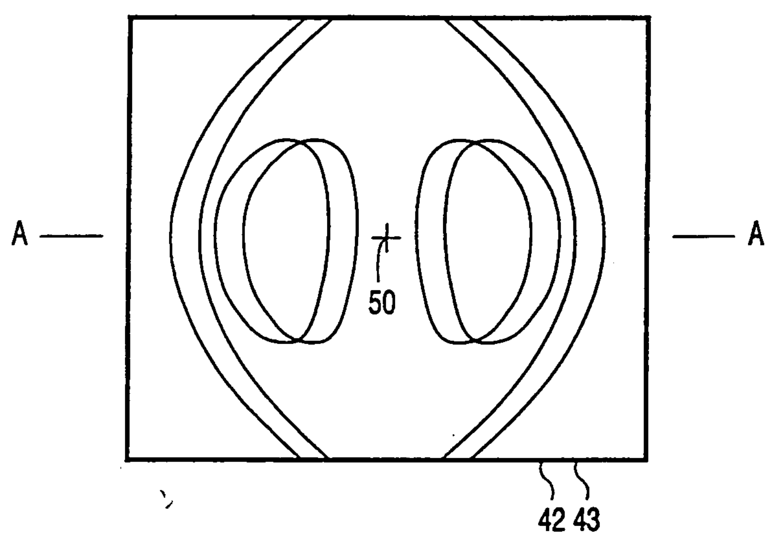

FIG. 4B

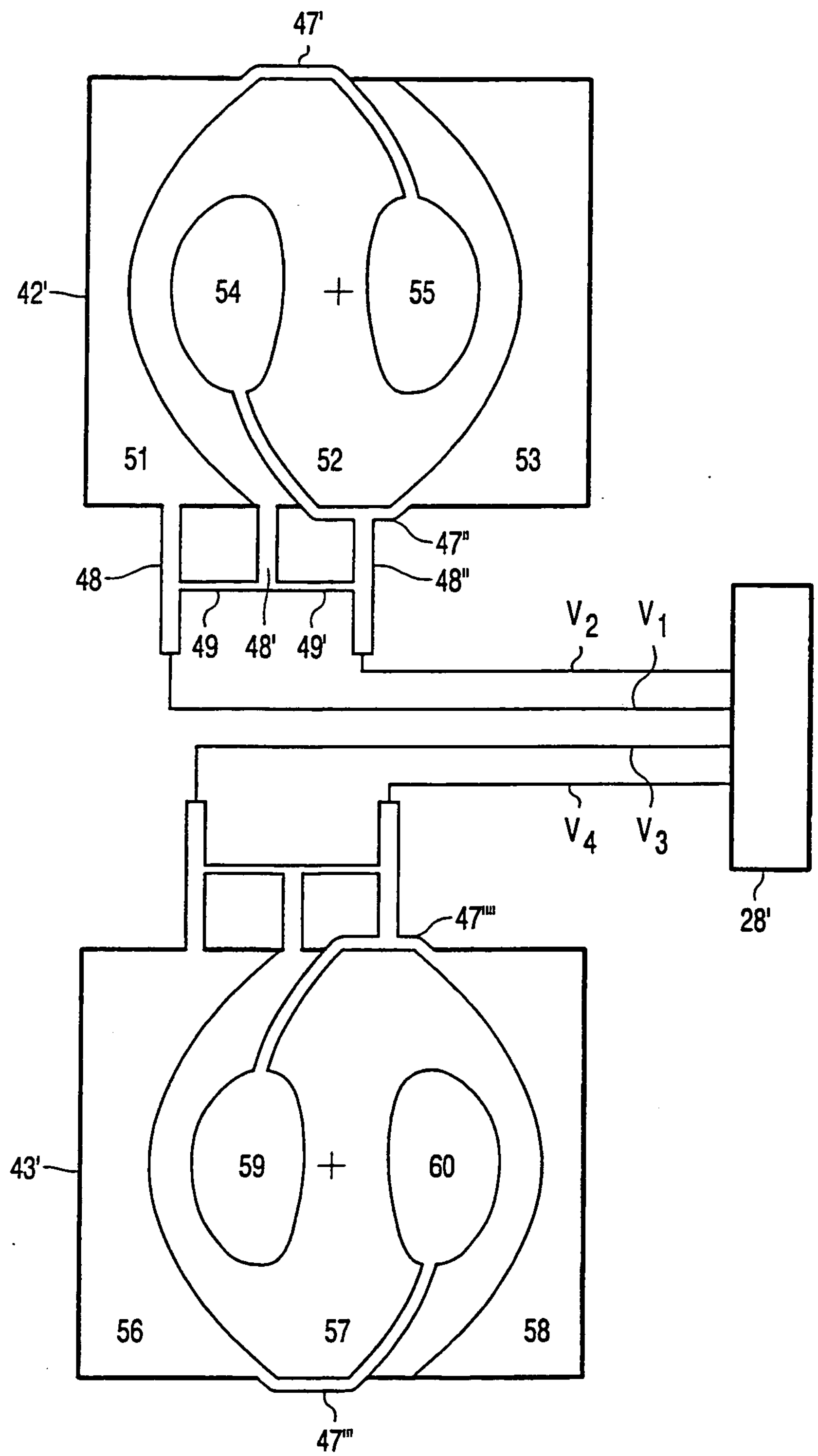
47'
42'
54
55
51
52
53
47''
48
48''
49
48'
49'
V_2
V_1
V_4
V_3
28'
47''''
43'
59
60
56
57
58
47'''

FIG. 5

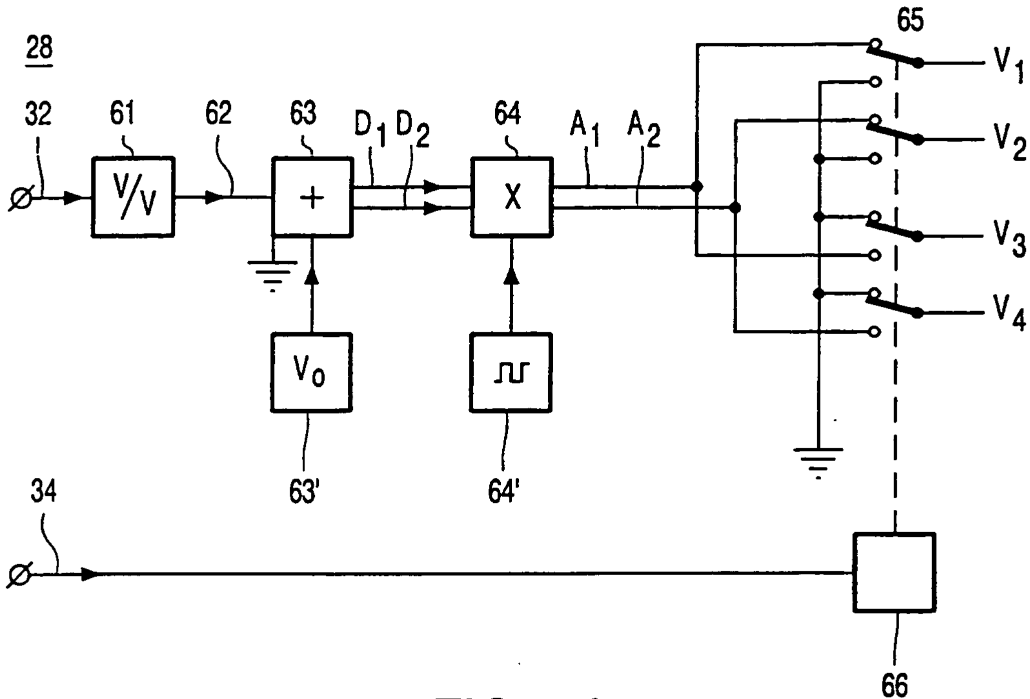
28
32
61
V/V
62
63
+
D1
D2
64
X
A1
A2
65
V1
V2
V3
V4
V0
63'
64'
34
66

FIG. 6A

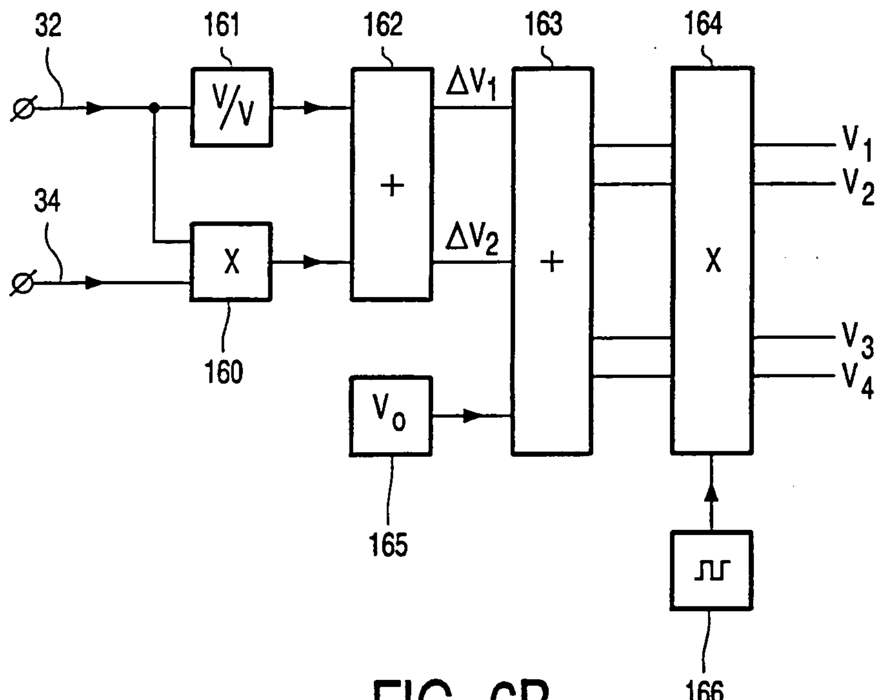
32
161
V/V
162
+
ΔV1
163
+
164
X
V1
V2
34
X
ΔV2
160
V3
V4
V0
165
166

FIG. 6B

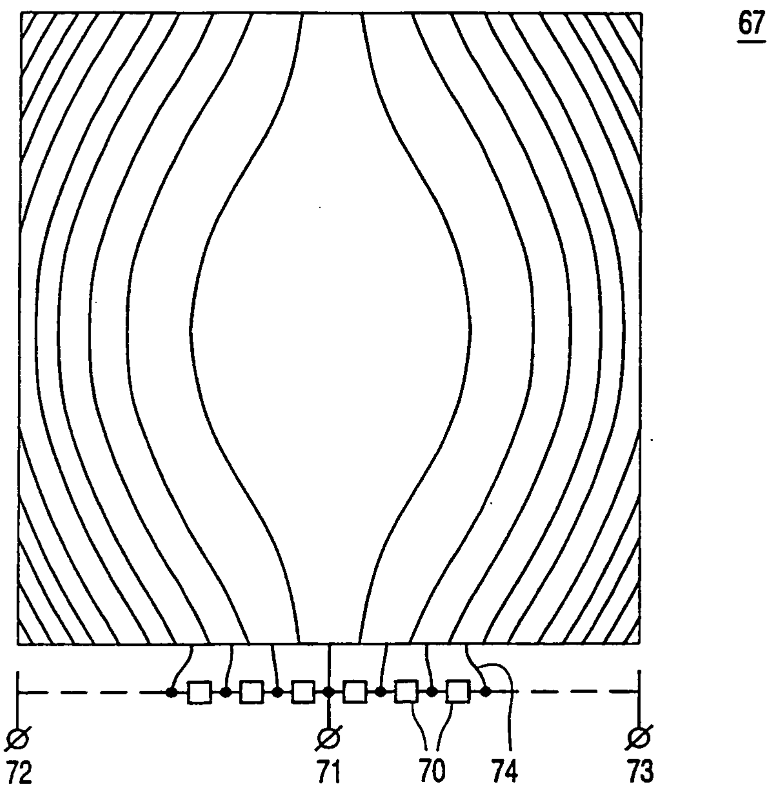

FIG. 7

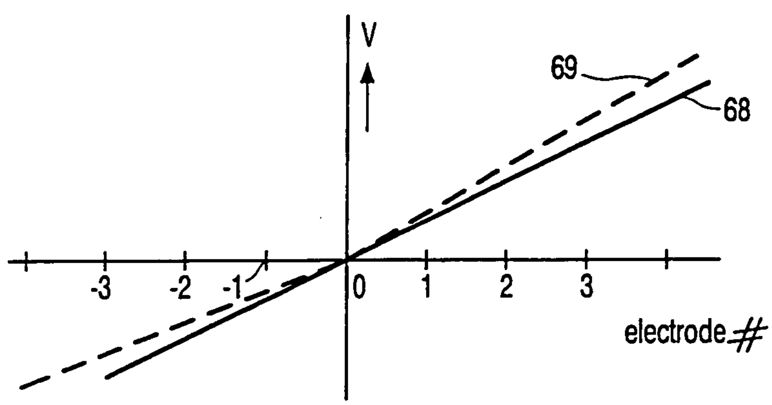

FIG. 8A

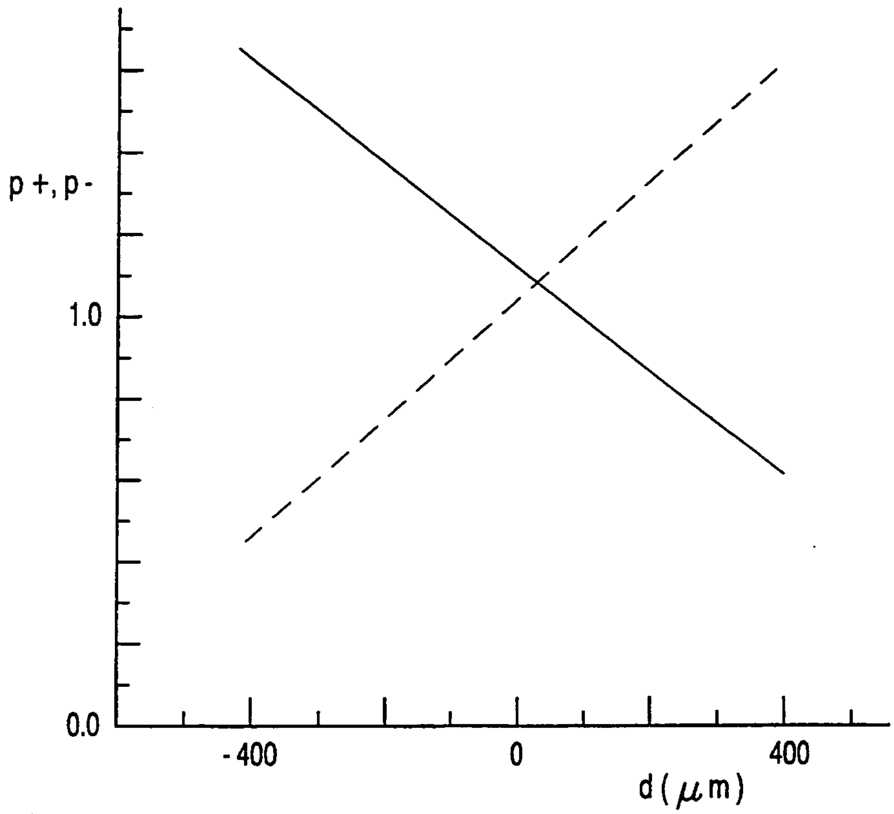

FIG. 8B

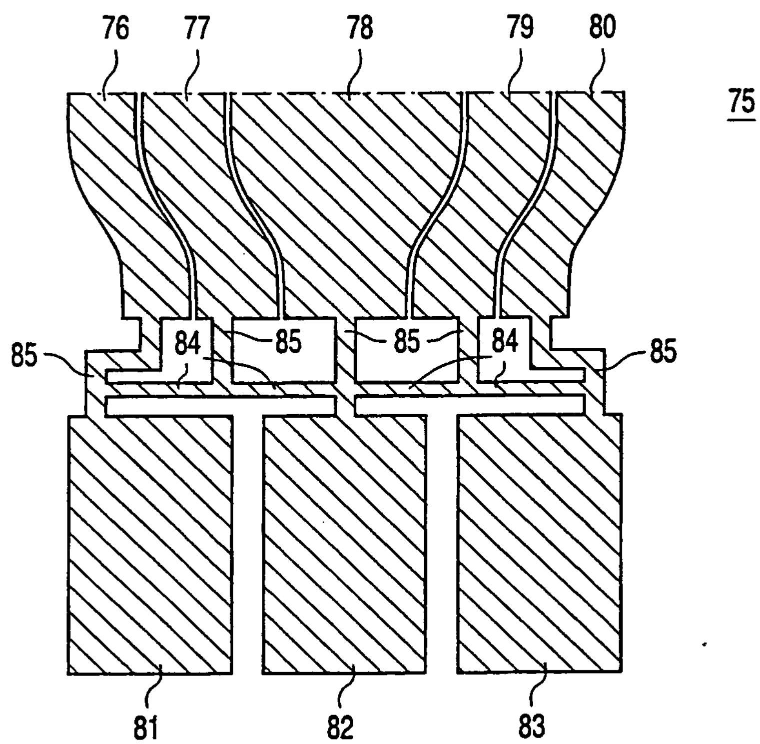

FIG. 9

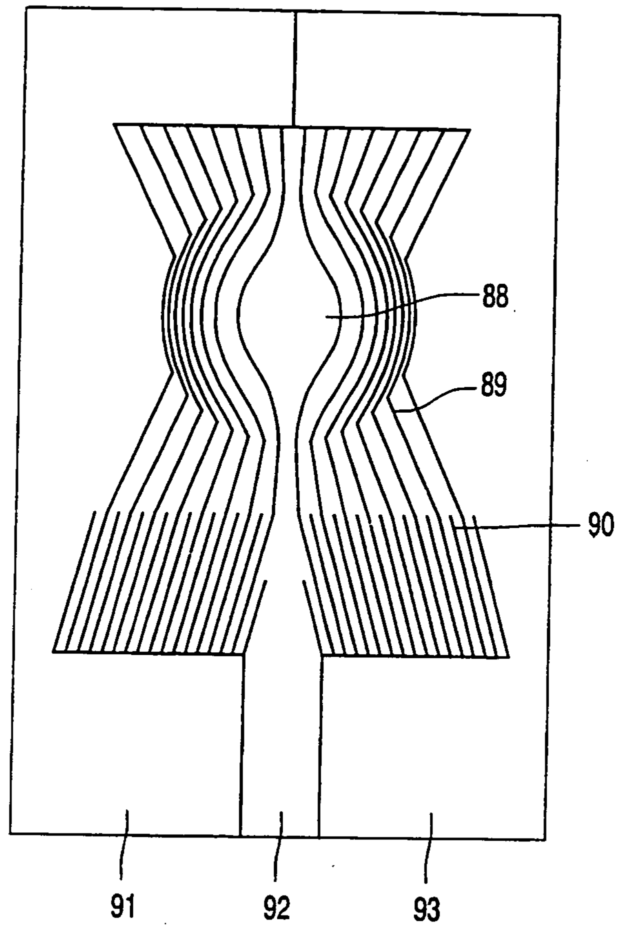

FIG. 10

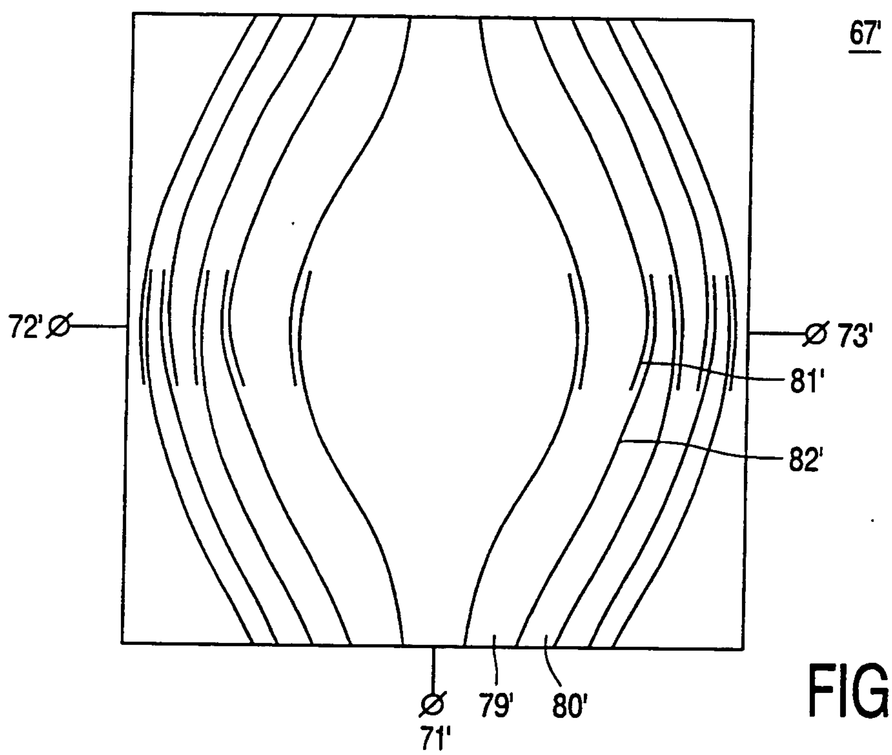

FIG. 11

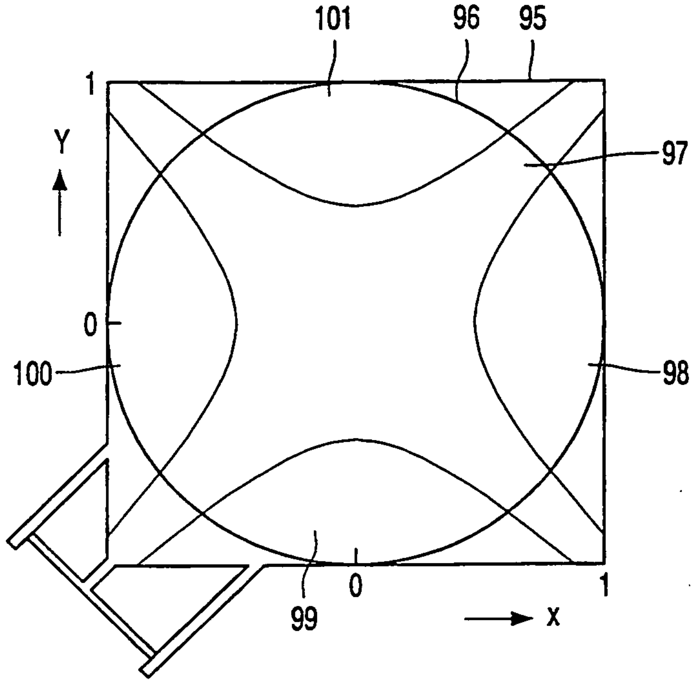
101
96
95
1
Y
97
0
100
98
99
0
1
x

FIG. 12

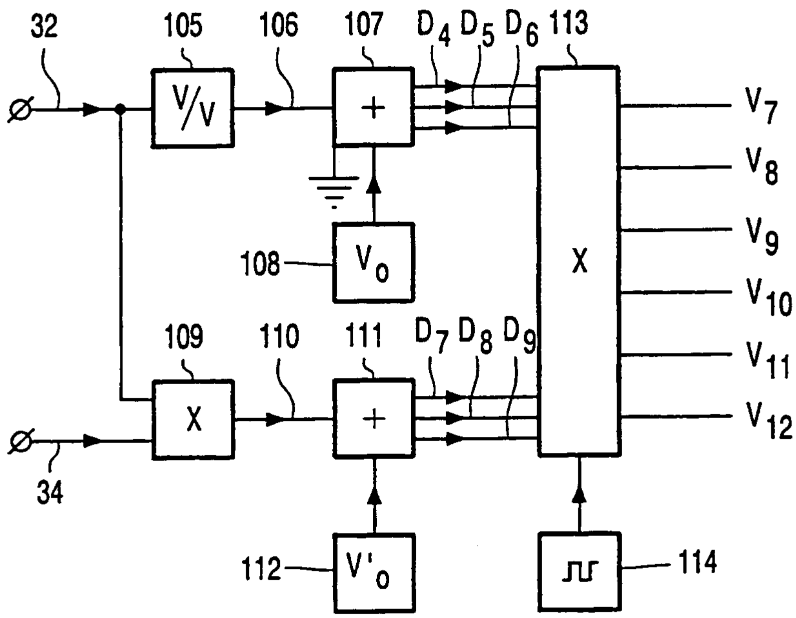
32
105
106
107
D_4 D_5 D_6
113
V/V
+
V_7
V_8
V_9
V_{10}
V_{11}
V_{12}
108
V_o
X
109
110
111
D_7 D_8 D_9
X
+
34
112
V'_o
114

FIG. 13

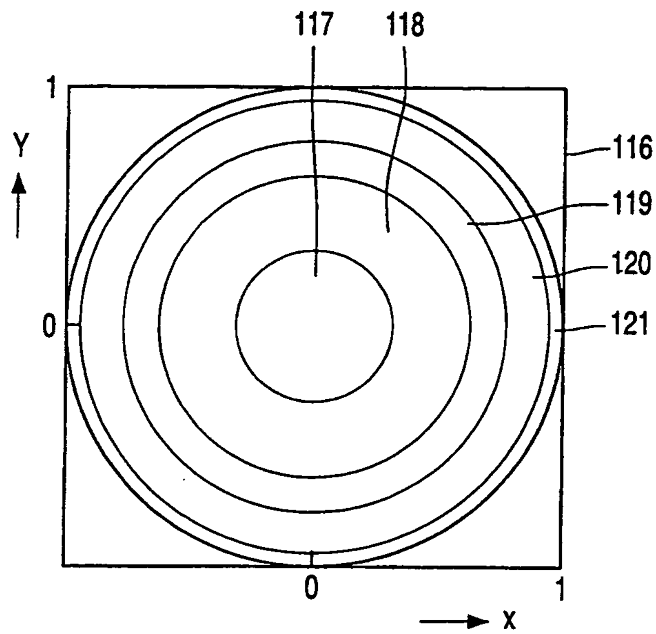

FIG. 14

Optical scanning device.

The invention relates to an optical scanning device for scanning an optical record carrier comprising an information layer, the device comprising an objective lens for converging a first radiation beam to a spot on the information layer.

An optical scanning device of the this type is known from the article ATilt correction in an optical system≅ by Gerber and Mansuripur, Applied Optics, Vol. 35, No. 35, pp. 7000-7007. In the known device a radiation source generates a radiation beam, which is converged to a spot on an information layer by an objective lens. The radiation beam reflected from the record carrier falls on a detection system. The electric output signals of the detection system are used to form a tilt signal, representing the tilt between the normal on the record carrier and the optical axis of the objective system. The tilt causes a comatic aberration of the spot. The tilt signal is used to control a tilt corrector arranged in the path of the first beam to compensate the comatic aberration. It is a disadvantage of the known scanning device that the quality of the spot is not sufficient when scanning high-density optical record carriers.

It is an object of the invention to provide a scanning device that does not have the above disadvantage.

The object is achieved in accordance with the invention by a scanning device as described in the opening paragraph, that is characterized in that it comprises a first and a second detection system for receiving a second radiation beam from the record carrier and arranged before and after an image of the spot, respectively, the detection systems being adapted for determining an intensity profile of incident radiation, and in that in also comprises an electronic circuit connected to electric outputs of the first and second detector for forming an electric signal representing a wavefront aberration of the second radiation beam.

The invention is based on the insight that the optical aberrations in the second beam may be determined from a measurement of the intensity profile of the radiation beam at a position before the image of the spot and at a position after the image of the spot. The value of an optical aberration can be determined from a combination of intensity values of both detection systems. If the second beam is split into two branches and the first and second detection system are arranged in the first and second branch, respectively, both detection systems should receive radiation from the same cross-section of the second beam to ensure

proper determination of the wavefront aberration. The measured values of the aberrations allow control of optical elements in the path of the radiation beam that compensate the effect of the aberrations, thereby improving the quality of the spot formed by the beam on the record carrier. The optical aberrations are the primary aberrations, such as spherical aberration, coma and astigmatism, and higher-order aberrations. It should be noted that optical aberrations do not include defocus.

A special embodiment of the detection system comprises a central detector, preferably arranged on the optical axis of the second beam, and an annular detector arranged around the central detector. Such a detection system is very suitable for the detection of spherical aberration in the second beam and also allows determination of the focus error.

Another embodiment of the detection system comprises three strip detectors. The detection system allows the determination of both the focus error and spherical aberration. It is also relatively insensitive to changes in the wavelength of the radiation. Such changes affect the path of the radiation beams, in particular where gratings or holograms are used. Other embodiments are given in the Claims.

It is noted that an optical scanning device having two detection systems, one before and one after an image of the spot, is known from the American patent no. 4,724,533. The electric detection signals of the first and second detection systems are used for forming a focus error signal, representing the axial distance between the focus of the first radiation beam and the position of the information layer. The detection signals are not used for forming signals representing optical aberrations in the second beam.

The objects, advantages and features of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings, in which

Figure 1 shows a scanning device;

Figure 2 shows an objective lens and a plano-convex lens;

Figure 3A, B, C show three embodiments of the detection systems and the division of a radiation beam over the detection systems;

Figure 4 shows the layout of detectors in an embodiment of the detection system;

Figure 5 shows a scanning device according to the invention;

Figure 6 shows the layout of detectors in an embodiment of the detection system; and

Figure 7 shows a graphical presentation of normalised spherical aberration signal as a function of the amount of spherical aberration introduced in the radiation beam under investigation.

Figure 1 shows a device for scanning an optical record carrier 1. The record carrier comprises a transparent layer 2, on one side of which an information layer 3 is arranged. The side of the information layer facing away from the transparent layer is protected from environmental influences by a protection layer 4. The side of the transparent layer facing the device is called the entrance face 5. The transparent layer 2 acts as a substrate for the record carrier by providing mechanical support for the information layer. Alternatively, the transparent layer may have the sole function of protecting the information layer, while the mechanical support is provided by a layer on the other side of the information layer, for instance by the protection layer 4 or by a further information layer and transparent layer connected to the information layer 3. Information may be stored in the information layer 3 of the record carrier in the form of optically detectable marks arranged in substantially parallel, concentric or spiral tracks, not indicated in the Figure. The marks may be in any optically readable form, e.g. in the form of pits, or areas with a reflection coefficient or a direction of magnetization different from their surroundings, or a combination of these forms.

The scanning device comprises a radiation source 6, for example a semi-conductor laser, emitting a diverging radiation beam 7. A beam splitter 8, for example a semi-transparent plate, reflects the radiation towards a lens system. The lens system comprises a collimator lens 9, an objective lens 10 and a plano-convex lens 11. The collimator lens 9 changes the diverging radiation beam 7 to a collimated beam 12. The objective lens 10, having an optical axis 13, transforms the collimated radiation beam 12 into a converging beam 14 incident on the lens 11. The collimator lens 9 and the objective lens 10 may be combined into a single lens. The plano-convex lens 11 changes the incident beam 14 into a converging beam 15, which comes to a spot 16 on the information layer 3. The plano-convex lens 11 has a convex surface and a flat surface. The flat surface faces the transparent layer 2 and forms a gap between the lens and the layer. Although the objective lens 10 is indicated in the Figure as a single lens element, it may comprise more elements, and may also comprise a hologram operating in transmission or reflection, or a grating for coupling radiation out of a waveguide

carrying the radiation beam. Radiation of the converging beam 15 reflected by the information layer 3 forms a reflected beam 17, which returns on the optical path of the forward converging beam 14. The objective lens 10 and the collimator lens 9 transform the reflected beam 17 to a converging reflected beam 18, and the beam splitter 8 separates the forward and reflected beams by transmitting at least part of the reflected beam 18 towards detection systems, generally indicated by a single element 19 in the Figure. The detection systems capture the radiation and convert it into electrical signals. One of these signals is an information signal 20, the value of which represents the information read from the information layer 3. Another signal is a focus error signal 21, the value of which represents the axial difference in height between the spot 16 and the information layer 3. The focus error signal is used as input for a focus servo controller 22, which controls the axial position of the objective lens 10 and/or the plano-convex lens 11, thereby controlling the axial position of the spot 16 such that it coincides substantially with the plane of the information layer 3. The part of the detection systems, including one or more radiation-sensitive detection elements and an electronic circuit processing the output signal of the detection elements, used for generating the focus error is called the focus error detection system. The focus servo system for positioning the lens system comprises the focus error detection system, the focus servo controller and an actuator for moving the lens system.

The actuator of the lens 10 is controlled by the focus error signal 21 to keep the spot 16 on the information layer 3. The spherical aberration which arises when the radiation beam has to be focused through a transparent layer which is thicker than the design thickness of the layer, is compensated for by a change in the distance between the objective lens 10 and the plano-convex lens 11. The distance between the two lenses is controlled by a signal representing a deviation from a nominal value of the spherical aberration as generated by the transparent layer in the radiation beam.

Figure 2 shows an enlargement of the objective lens 10 and the plano-convex lens 11. The objective lens 10 may be a mono-aspherical plano-convex lens or a bi-aspherical lens . The objective lens 10 is designed in a known way to compensate for the spherical aberration introduced by the plano-convex lens 11 and a transparent layer 2 having a nominal thickness, thereby making the radiation beam near the spot 16 nominally substantially free from spherical aberration.

If the spot 16 is properly positioned on the information layer 3 and no optical aberrations are introduced in the optical path from the radiation source 6 to the detection systems 19, the wavefront of the reflected beam 18 will be spherical and the beam 18 is

unaberrated. Since rays of a beam travel in a direction normal to its wavefront, the rays of the unaberrated beam will travel toward the Gaussian focus, which in the case of a properly focused beam 15 is the image of the spot 16, lying on the optical axis. Any deviation of the wavefront from spherical will cause rays to deviate from the paths of an unaberrated rays, and cause them to travel not toward the Gaussian focus, resulting in changes in the spatial intensity distribution of the beam 18 different from the intensity distribution of the unaberrated beam. The changes in the intensity distribution do not only depend on the type of optical aberration present in the beam 18, but also on the distance from the Gaussian focus. In principle, knowledge of both the intensity distribution of the aberrated beam 18 and of the unaberrated beam in a plane perpendicular to the optical axis suffices to determine the optical aberration of the beam. However, knowledge of the intensity distribution of the unaberrated beam is not available in general. It turns out that a measurement of the intensity distribution in a plane before the Gaussian focus and in a plane after the Gaussian focus provides sufficient information to determine the optical aberration of the beam 18. This is due to the fact that the effect of the deviating path of the rays is different in planes at different positions along the optical axis, and that a comparison of intensities in corresponding positions in each plane can give a result that is insensitive to the actual intensity distribution of the unaberrated beam.

The determination of the value of the aberrations will be simplified if the distance of both planes from the Gaussian focus is equal. The distance between the plane of each detection system and the Gaussian focus is preferably larger than the Raleigh length of the beam 18. The Raleigh length R_l is a distance from Gaussian focus corresponding to $(\pi o2)^{-1}$ wavelengths, i.e. 225 mλ, defocus in terms of the Zernike polynomial R_2^0. If the value of the defocus for a particular plane is equal to A_{20}, the distance of the plane from the Gaussian focus is equal to $2(o2)A_{20}\lambda(NA)^{-2}$ according to the Zernike formalism for describing wavefront aberrations. The Raleigh length is then $2\lambda(\pi NA)^{-2}$, where λ is the wavelength of the radiation and NA is the numerical aperture of the beam 18.

Figures 3A, B and C show embodiments of detection systems 19 and the division of the reflected beam 18 over two detection systems. One detection system is arranged before the Gaussian focus and one detection system after the Gaussian focus in order to determine the wavefront aberrations in the beam 18. The position of the Gaussian focus corresponds to the position of the image of spot 16 if the beam 18 is unaberrated and beam 15 is properly focussed on the information layer 3.

In Figure 3A a beam splitter 25 in the form of a semi-reflecting layer divides the beam 18 into two sub-beams 26 and 27. A detection system 28 is arranged in the sub-beam

26 before the focus 29 of the beam 26. A detection system 30 is arranged in the sub-beam 27 after the focus 31 of the beam 27. The focus 29 and 31 correspond to the image of the spot 16 on the record carrier as formed by the lenses 9, 10 and 11.

Figure 3B shows a holographic optical element 32 for splitting the incoming beam 18 as diffracted -1st, 0th and +1st orders into three sub-beams 33, 34 and 35. Detection systems 36 and 37 are arranged in the paths of the sub-beams 33 and 35 , respectively. To arrange one detection system before and one after the focus of the sub-beam, the detection systems may be arranged at different distances from the holographic element 32. Alternatively, as shown in the Figure, the holographic element 32 may have optical strength for the -1st and +1st order diffracted beams. In that case the detection systems 36 and 37 may be arranged in the same plane, and the sub-beam 33 comes to a focus 38 before the detection system 36 and the sub-beam 35 comes to a focus 39 after the detection system 37. The 0th order sub-beam 34 may be used for detecting defocus and tracking error and for generating an information signal.

Figure 3C shows an embodiment in which the detection systems 40 and 41 may be arranged in the same plane. An optical prism element 42 divides the incoming radiation beam 18 into two sub-beams 42 and 43. The difference in path length from the plane of division 45 to the two detection systems 43 and 44 causes the sub-beam 43 to come to a focus 46 after the detection system 40 and the sub-beam 44 to a focus 47 before the detection system 41.

Figure 4 shows a plan view of the detection system 28 shown in Figure 3A. The detection system 30 has the same layout. The detection system comprises five detectors, i.e. a detector 51 arranged on the optical axis of the beam 18, two detectors 52a and 52b arranged on both sides of the optical axis and parallel to the effective track direction and two detectors 53a and 53b arranged on both sides of the optical axis and perpendicular to the effective track direction. The effective track direction is the direction of the image of a track of the record carrier formed on the detection system. The detectors of the detection system 30 are numbered in the same way as the detectors of the detection system 28. If the detection system 30 can be regarded as positioned effectively below the detection system 28 with its light-sensitive surface facing the beam 18 and without rotating the detection system around the normal on its light-sensitive surface; in that position equally numbered detectors are effectively superjacent. Since the beam 18 passes through a focus in between the two detection systems, corresponding detectors on the two detection systems are effectively arranged crosswise. The position of the

detectors in the detection systems 28 and 30 are adapted for determining the spherical aberration and coma in the beam 18.

The detection systems 28 and 30 in Figure 3A having a detector layout as shown in Figure 4 can be used to determine the amount of spherical aberration present in the beam 18. Thereto the difference signal is formed of the output signals of corresponding detectors in the detection systems 28 and 30, i.e. the difference between the output signal of central detectors 51, the difference signal of the effectively crosswise located detectors 52a in the detection system 28 and 52b in the detection system 30, and that of the effectively crosswise arranged detectors 53b in the detection system 28 and 53a in the detection system 30. The amount of spherical aberration is linearly related to difference signals. In order to reduce the influence of variations in the intensity distribution of the beam 18 over the plane of the detection system, the difference signals are preferably normalized and combined to a spherical aberration signal S_{A40} as follows:

$$S_{A40} = \frac{I_1(51) - I_2(51)}{I_1(51) + I_2(51)} - \frac{I_1(52a) - I_2(52b)}{I_1(52a) + I_2(52b)} - \frac{I_1(52b) - I_2(52a)}{I_1(52b) + I_2(52a)}$$

where $I_1(x)$ and $I_2(x)$ are the signals representing the intensity measured by detector x in the detection system 28 and 30, respectively. Two terms similar to the terms for the detectors 52a and 52b but now for the detectors 53a and 53b may replace the terms for the detectors 52a and 52b or be added to the above expression. It will be clear that the signal S_{A40} not only gives the magnitude of the spherical aberration but also its sign.

The transparent layer 2 of the record carrier 1 causes coma in the beam 15 when the record carrier is tilted with respect to the optical axis 13 of the objective system. When the beam is reflected back through the transparent layer, the coma is cancelled. However, in the regions of the reflected beam where the $+1^{st}$ and -1^{st} diffracted orders from the record carrier overlap with the 0^{th} order, coma is still visible. The detectors of the two detection systems parallel to or perpendicular to the effective track direction may be used for deriving a signal representing coma due to tilt of the record carrier in a direction parallel or perpendicular to the track direction. Thereto the difference signal is formed of the output signals of corresponding detectors in the detection systems 28 and 30, i.e. the difference between the output signal of the two effectively superjacent detectors 53a and the difference signal of the two effectively superjacent detectors 53b in the detection systems 28 and 30. The amount of coma is related to the first difference signal minus the latter difference signal. In order to reduce the influence of variations in the intensity distribution of the beam 18 over the plane of the detection system,

the difference signals are preferably normalized and combined to a coma signal S_{A31} as follows:

$$S_{A31} = \frac{I_1(53a) - I_2(53a)}{I_1(53a) + I_2(53a)} - \frac{I_1(53b) - I_2(53b)}{I_1(53b) + I_2(53b)}$$

The layout of the detection systems 28 and 30 also allows the determination of the defocus, i.e. of the distance between the focus of beam 15 and the information layer 3. A defocus signal S_{A20} may be determined as follows:

$$S_{A20} = \frac{I_1(51) - I_2(51)}{I_1(51) + I_2(51)} + \frac{I_1(52a) - I_2(52b)}{I_1(52a) + I_2(52b)} + \frac{I_1(52b) - I_2(52a)}{I_1(52b) + I_2(52a)}$$

The influence of variations in the intensity distribution of the beam 18 over the plane of the detection system is reduced by normalization of the difference signals.
Since the spherical aberration and defocus interfere in the above determination as well as coma and track error, the simplest way to measure the spherical aberration and coma is to make the measurement when the defocus and track error, respectively, are substantially equal to zero. Thereto the defocus and track error should be measured separately by methods such as the known so-called astigmatic focus method and the push-pull method, respectively.

Figure 5 shows a scanning device with an alternative embodiment of the detection systems. A radiation source 60 emits a radiation beam 61, which is collimated by a collimator lens 62. The beam passes subsequently through a beam splitter 63, an adaptive optical element 64 and a quarter-wave plate 65 before being converged by an objective lens 66 through a transparent layer 67 of a record carrier 68 to a spot 69. The quarter-wave plate converts the linearly polarized incident beam into a circularly polarized beam. The beam 72 reflected from the record carrier is coupled out of the path of the beam 61 by the polarizing beam splitter 63 and converged by a lens 70 to a prism element 71. The prism element divides the beam into two sub-beams, one focused before a detection system 74 and one focused behind a detection system 73. The Figure also shows the detection systems 74 and 73 in plan view. Each detector system comprises a split central detector, indicated by elements 73a, 73b and 74a, 74b. A split annular detector is arranged around the central detector, indicated by elements 73c, 73d and 74c, 74d. The detectors are split along the effective track direction. The layout of the detectors is adapted for the determination of the spherical aberration. The layout also allows the determination of the defocus and the tracking error.

The signal S_{A40} representing the spherical aberration may be derived as follows:

$$S_{A40} = \frac{(I_{73c} + I_{73d}) - (I_{74c} + I_{74d})}{(I_{73c} + I_{73d}) + (I_{74c} + I_{74d})} - \frac{(I_{73a} + I_{73b}) - (I_{74a} + I_{74b})}{(I_{73a} + I_{73b}) + (I_{74a} + I_{74b})}$$

where I_x is the signal representing the intensity measured by detector x. Figure 5 shows an implementation of the derivation of S_{A40}, without normalisation, by means of adders 76-79 and subtractors 80-82. The spherical aberration signal is used to control the adaptive optical element 64, which may have the form of a liquid crystal device or a piezo-electric device affecting the phase of the wavefront. The adaptive optical element may also be a deformable mirror.

The signal A_{20} representing the defocus or focus error may be derived as

$$S_{A20} = -\frac{(I_{73a} + I_{73b}) - (I_{74a} + I_{74b})}{(I_{73a} + I_{73b}) + (I_{74a} + I_{74b})}$$

By using only the central detectors 73a, 73b, 74a and 74b for determining the defocus, a defocus signal is obtained, which is relatively insensitive to the presence of spherical aberration. Figure 5 shows an implementation of the derivation of S_{A20} without normalisation by means of adders 76 and 77 and subtractor 80. In the embodiment of Figure 5 the difference of the signals from the annular detectors 73c, 73d, 74c and 74d suffices for the determination of the spherical aberration signal, because the focus servo circuit maintains the difference of the signals from the central detectors at a zero value. The defocus signal is used to control an actuator 83. The actuator can change the axial position of the objective lens 66 and its transverse position. The defocus signal is used to control the axial position.

The signal S_{TE} representing the tracking error, i.e. the deviation between the centre of the spot 16 and the centre line of a track to be scanned in the information layer 3, may be derived according to the push-pull method:

$$S_{TE} = \frac{(I_{73b} + I_{73d}) - (I_{73a} + I_{73c})}{(I_{73b} + I_{73d}) + (I_{73a} + I_{73c})} + \frac{(I_{74b} + I_{74d}) - (I_{74a} + I_{74c})}{(I_{74b} + I_{74d}) + (I_{43a} + I_{74c})}$$

The tracking error signal is used to control the transverse position of the objective lens 66, as schematically indicated in Figure 5. Figure 5 shows an implementation of the derivation of S_{TE} without normalisation by means of adders 84-87 and 90 and subtractors 88 and 89. If the scanning device must scan record carriers having a small push-pull signal, the tracking error signal is preferably derived according to the so-called DTD method and each central and

annular detector is not divided into two detectors as shown in Figure 5 but into four quadrant detectors.

The diameter of the central detectors 73a plus 73b and 74a plus 74b is preferably substantially equal to 35% of the diameter of the spot formed by the beam incident on the detection systems if the beam is free from aberrations. The inner and outer diameter of the annular detectors 73c plus 73 d and 74c plus 74d is preferably substantially equal to 55% and 80%, respectively, of the spot diameter of the unaberrated incident beam. These dimensions provide an optimum spherical aberration signal.

Figure 6 shows two detection systems 95 and 96, which may be used in the embodiments shown in Figure 3A, 3B and 3C. Each detection system comprises three parallel strip detectors, indicated by 95a, 95b, 95c, 96a, 96b and 96c. Circles 9.7 and 98 indicate the cross-section of the unaberrated beam in the plane of the detection system. The circle segments 99 indicate the area of overlap between the 0^{th} order beam and the -1^{st} and $+1^{st}$ order beam diffracted by the track structure of the record carrier. Shaded ring 100 is the area of higher intensity in the intensity distribution on the detection system when the beam suffers from spherical aberration. Circle 101 is the corresponding area of higher intensity on the other detector due to the same spherical aberration. The sizes of these areas relative to the size of the unaberrated beam are relatively independent of the location of the detection system on the optical axis. The layout of the detectors is adapted to the determination of the spherical aberration, defocus and tracking error. When the amount of radiation emitted by a semiconductor laser or the temperature of the laser is changed, the wavelength of the emitted radiation also changes. As a consequence, in a scanning device where the beams incident on the detection systems are formed by a diffractive element, such as a hologram or grating, the position of the spot on the detection systems also changes. Since a displacement of the intensity distribution along the division lines of the detectors shown in Figure 6 does not affect the output signal of the detectors, the detection systems are very suitable for use in such a scanning device, provided the division lines between the strip detectors is substantially perpendicular to the direction of the grating lines of the diffractive element.

The signal S_{A40} representing the spherical aberration may be derived as follows:

$$S_{A40} = \frac{I_{95b} - I_{96b}}{I_{95b} + I_{96b}} - \frac{I_{95a} + I_{95c} - I_{96a} - I_{96c}}{I_{95a} + I_{95c} + I_{96a} + I_{96c}}$$

where I_x is the signal representing the intensity measured by detector x. The defocus signal S_{A20} may be obtained in the following way:

$$S_{A20}=\frac{(I_{95a}+I_{95c}+I_{96b})-(I_{96a}+I_{96c}+I_{95b})}{(I_{95a}+I_{95c}+I_{96b})+(I_{96a}+I_{96c}+I_{95b})}$$

The tracking error S_{TE} can be derived as:

$$S_{TE}=\frac{(I_{95a}+I_{96c})-(I_{95c}+I_{96a})}{(I_{95a}+I_{96c})+(I_{95c}+I_{96a})}$$

The combination of detector signals makes the error and aberration signals relatively insensitive to displacement of the radiation beam in a direction perpendicular to the dividing lines between the detectors.

The width of the strip detectors 95b and 96b is preferably equal to 35% of the diameter of the cross-section of the unaberrated beam, i.e. substantially equal to the width of area 101. The width of the neighbouring strip detectors 95a, 95c, 96a and 96c may be from 35% to 100% of the radius of the cross-section. An increase in the spherical aberration signal will be obtained if the width of the neighbouring detectors is from 35% to 80% of the radius of the cross-section. A further increase in the spherical aberration signal may be obtained if the width of the neighbouring detectors is from 55% to 80%, thereby having a width substantially equal to the width of the ring 100.

Figure 7 shows a graphical presentation of the normalised spherical aberration signal S_{A40} as a function of the amount A_{40} of spherical aberration introduced in the radiation beam incident on the detection systems. The wavelength of the radiation beam is 650 nm, the distance between each detection system and the Gaussian focus is equal to 760 μm, corresponding to 5 λ defocus. The numerical aperture of the beam incident on the record carrier is 0.60 and that of the beam incident on the detection systems is equal to 0.11. Curve 105 represents the normalised response of the circular detection system 73 and 74 as shown in figure 5. Curve 106 is the response of the detection systems 95 and 96, where the detectors 95a, 95c, 96a and 96c have a width from 55% to 80% of the radius of the cross-section of the unaberrated beam; i.e. the distance between the centre of the detectors 95a, 95c, 96a and 96c and the centre of the central detectors 95b and 96b is substantially equal to 67% of the radius. Curve 107 is similar to curve 106, but the width is from 35% to 80%, whereas the width in the detection system of curve 108 is from 35% to 100%. The Figure shows that the narrowing of the strip detector width increases the normalised response.

Curve 105 of Figure 7 shows that the response of the circular detection systems at a mutual distance of 10 λ defocus reaches a maximum value for a spherical aberration of

approximately 1 λ. Hence, the detection system can measure spherical aberration up to 1 λ. In general, the amount of spherical aberration increases linearly with the distance between the two detection systems. The distance between the two detection systems is preferably equal to 10 A defocus if the measurement range for spherical aberration is from -A to +A; this value is in particular suitable for ring-shaped detection systems as shown in Figure 5. The distance is more preferably equal to 5 A defocus; this is in particular suitable for detection systems having strip detectors as shown in Figure 6.

The information signal , representing information stored on the record carrier, may be derived from a sum of the output signals of the separate detectors of both detection systems. In a special embodiment of the scanning device the information signal is a sum of the output signals of the central detectors of both detection systems. A scanning device comprising a third sub-beam divided from the reflected beam may use this third beam for generating the information signal. It will be clear to the skilled person, that the layout of any of the detection systems 28, 30, 36, 37, 40, 41 may be similar to that of detection system 28, 73 or 97.

CLAIMS:

1. An optical scanning device for scanning an optical record carrier comprising an information layer, the device comprising an objective lens for converging a first radiation beam to a spot on the information layer, characterized in that it comprises a first and a second detection system for receiving a second radiation beam from the record carrier and arranged before and after an image of the spot, respectively, the detection systems being adapted for determining an intensity profile of incident radiation, and in that in also comprises an electronic circuit connected to electric outputs of the first and second detector for forming an electric signal representing a wavefront aberration of the second radiation beam.

2. Optical scanning device according to Claim 1, wherein the distance between the first detection system and the image of the spot is substantially equal to the distance between the image of the spot and the second detection system.

3. Optical scanning device according to Claim 1, wherein the distance between the first or second detection system and the image of the spot is larger than the Raleigh length of the second radiation beam.

4. Optical scanning device according to Claim 1 or 2, wherein the first and second detection system each comprise a plurality of detectors and the electronic circuits is arranged for forming a difference signal between detector signals of corresponding detectors of the first and second detection system.

5. Optical scanning device according to Claim 4, wherein each of the plurality of detectors has a position within the appropriate detection system corresponding to the wavefront aberration to be determined.

6. Optical scanning device according to Claim 5, wherein each detection system comprises a detector arranged on the optical axis of the second radiation beam and a detector arranged at a position removed from the optical axis.

7. Optical scanning device according to Claim 1, wherein the first and second detection system each comprise a central detector centred on the optical axis of the second beam and an annular detector arranged around it.

8. Optical scanning device according to Claim 7, wherein the central detector and the annular detector are each split in two sub-detectors.

9. Optical scanning device according to Claim 1, wherein each detection system comprises a central strip detector and two neighbouring strip detectors.

10. Optical scanning device according to Claim 9, wherein the central detector is arranged on the optical axis of the second beam.

11. Optical scanning device according to Claim 9, wherein the width of the central strip detector is substantially equal to 0.35 times the diameter of a non-aberrated second beam at the axial position of the central detector.

12. Optical scanning device according to Claim 9, wherein the distance between the centre of the neighbouring strip detector and the optical axis is substantially equal to 0.67 times the radius of a non-aberrated second beam at the axial position of the central detector.

13. Optical scanning device according to Claim 9, wherein the width of the neighbouring strip detector is substantially equal to 0.25 times the radius of a non-aberrated second beam at the axial position of the central detector.

14. Optical scanning device according to Claim 1 having a measurement range for spherical aberration from -A to +A, wherein the distance between the first and second detection system is substantially equal to 10 A defocus in Zernike terms of the second radiation beam.

ABSTRACT:

An optical scanning device for scanning a record carrier (68) directs a radiation beam (61) towards the record carrier. Two detection systems (73, 74) are arranged in the path of the beam (72) reflected by the record carrier, one before and one after the focus of the beam. Output signals of the detection systems represent the intensity distribution of the beam in the plane of each detection system. The output signals are processed to form a signal representing an aberration of the reflected beam. The aberration may be coma or spherical aberration. The aberration signal is used to control a compensation element (64) in the optical path of the radiation beam incident on the record carrier.

Figure 5

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INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference PHN 17.843WO	**FOR FURTHER ACTION** see Notification of Transmittal of International Search Report (Form PCT/ISA/220) as well as, where applicable, item 5 below.	
International application No. PCT/EP 00/ 12991	International filing date *(day/month/year)* 19/12/2000	(Earliest) Priority Date *(day/month/year)* 24/12/1999
Applicant KONINKLIJKE PHILIPS ELECTRONICS N.V.		

This International Search Report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This International Search Report consists of a total of 3 sheets.

[X] It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**

a. With regard to the **language,** the international search was carried out on the basis of the international application in the language in which it was filed, unless otherwise indicated under this item.

[ ] the international search was carried out on the basis of a translation of the international application furnished to this Authority (Rule 23.1(b)).

b. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international search was carried out on the basis of the sequence listing :

[ ] contained in the international application in written form.
[ ] filed together with the international application in computer readable form.
[ ] furnished subsequently to this Authority in written form.
[ ] furnished subsequently to this Authority in computer readble form.
[ ] the statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.
[ ] the statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished

2. [ ] **Certain claims were found unsearchable** (See Box I).

3. [ ] **Unity of invention is lacking** (see Box II).

4. With regard to the **title,**

[X] the text is approved as submitted by the applicant.
[ ] the text has been established by this Authority to read as follows:

5. With regard to the **abstract,**

[X] the text is approved as submitted by the applicant.
[ ] the text has been established, according to Rule 38.2(b), by this Authority as it appears in Box III. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.

6. The figure of the **drawings** to be published with the abstract is Figure No. 5

[X] as suggested by the applicant.
[ ] because the applicant failed to suggest a figure.
[ ] because this figure better characterizes the invention.

[ ] None of the figures.

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 00/12991

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G11B7/135 G02F1/1343

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G11B G02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	EP 1 011 009 A (MATSUSHITA ELECTRIC IND CO LTD) 21 June 2000 (2000-06-21) column 9, line 45 -column 10, line 5; claim 1; figure 3	1,2,5
A	US 5 936 923 A (OOTAKI SAKASHI ET AL) 10 August 1999 (1999-08-10) the whole document	1
A	EP 0 911 681 A (SEIKO EPSON CORP) 28 April 1999 (1999-04-28) claims 1-3; figure 1	1
A	GB 2 276 465 A (MARCONI GEC LTD ;PURVIS ALAN (GB)) 28 September 1994 (1994-09-28) claim 1; figure 1	1

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search	Date of mailing of the international search report
23 May 2001	30/05/2001

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 00/12991

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 859 818 A (MURAO NORIAKI ET AL) 12 January 1999 (1999-01-12) claim 1; figures 1,3 -----	1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/EP 00/12991

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